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ORIGINAL ARTICLE

Theoretical analysis of natural fiber volume fraction of reinforced composites

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KEYWORDS

Fibers;
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Fiber volume fraction;
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Packing density

Abstract In the latest years industry is attempting to decrease the dependence on petroleum based fuels and products due to the increased environmental consciousness. This is leading to the need to investigate environmentally friendly, sustainable materials to replace existing ones, and to solve the problems of recycling of agriculture waste. We are trying to understand composites due to their high potential as a material with suitable strength, low weight and low deformation. Fiber and epoxy as lamina are used to form composite laminates with desired directional properties. Mechanical properties for composites are derived starting from properties of fiber and matrix, using the rule of mixtures, and the fiber volume fraction plays a significant role in the determination of the mechanical properties. In this work the value of the fiber volume fraction is determined considering fibrous structure constituent, random fiber, yarns or fabric.

1. Introduction

Straw in clay constructions by Ancient Egyptians are certainly one of the oldest and most widely used composite materials. The need for renewable fiber reinforced composites has increased in the last decade. Natural fibers offer both cost savings and a reduction in density when compared to glass fibers. Though the strength of natural fibers is not as great as glass fibers, the specific properties are comparable. Natural fibers such as cotton, kenaf, and flax have the ability to form a good bond between thermoplastic binder polymers [1–4]. Recently, natural fibers have also been used in exterior composite components. Car manufactures have been interested in integrating natural fiber composites into both interior and exterior parts [1,5,6] based on use of natural fiber fabrics. Most studies on plant fiber composites have primarily focused on the fibrous structure and matrix part of the composites, not taken into consideration the porosity of these structures, considering the fibers as a solid rod as well as the yarns [7]. This may be true in the case of synthetic fibers. With synthetic fiber composites considerable knowledge has been built up to control the porosity content to be less than 2% normally. The fiber-volume fraction has a profound influence on interface failure [8–12]. However, in the case of natural fiber composites, the porous fiber structure makes a noteworthy contribution to

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the overall composite volume and properties. The natural fibers are able to absorb moisture and to keep it, so the weight of the natural fibers may increase by 40% depending on the relative humidity. The large water sorption capacity of plant fibers means that fiber density cannot be specified by a single value. Furthermore, their porous structure makes it necessary to distinguish between an absolute densities of the fiber solid matter [2] and an apparent that includes the central lumen of the fibers. The obtained flax composites, especially the unidirectional composites can be used in structural composites. Unidirectional flax composites have higher specific stiffness than glass fiber composites and high strength [8]. It has been also shown that composite parts of complex shape using continuous flax fiber reinforcements can be made by the conventional processing techniques without any modification in the equipment [11]. In the case of using yarns, which is a fibrous structure formed by twisting the fiber tuft together forming continuous twisted strand of fibers, the yarn structure is dependent primarily upon the raw material properties, type of spinning process, machine settings, twist, etc. [12]. The structure can be open or closed; voluminous or compact; smooth or rough or hairy; soft or hard; round or flat; thin or thick, etc. Several investigator [10,13–18] indicated that yarns spun from finer fibers have higher packing density at the same twist level due to higher relative fiber surface. Higher packing density means lower yarn diameter on one side and, on the other, higher number of inter-fiber contacts. The emphasis of research and development in the past half century has been on synthetic fibers and resins, and a matching effort is required to convey natural fiber composite advance structures into commercial availability. The present analysis investigated the fiber volume fraction for the different fiber structures hence it determines mechanical characteristics of the composite.

2. Analysis of the fiber volume fraction in natural fiber composites

Fig. 1 shows that NF composite may consist of loose fiber aggregate compressed in the thin layer and, in the case of short fibers, it will be randomly laid. However, for long fibers, they may be laid uni-directionally or multi-directionally in a several layers. Yarns may also be used as spun yarns parallel in one direction or orthogonally laid or they may be woven or knitted or braided to form a fabric in 2 D or 3D. In the case of using the synthetic fibers, they occupy the largest fraction of the composite and bear the major portion of the load. Consequently, the fiber volume fraction and fiber orientation play important role of the final composite characteristics. Usually, the synthetic fiber is different from the natural fiber in many characteristics such as the density, moisture absorption, and the cross section shape and the fiber morphology. In the case of NF composite, the matrix combines the fibers together, holding them aligned in the important stressed directions. Loads applied to the composite are then transferred into the fibers, the principal load-bearing component, through the matrix, enabling the composite to withstand compression, flexural and shear forces as well as tensile loads. The ability of composites reinforced with short fibers to support loads of any kind is dependent on the presence of the matrix as the load-transfer medium, and the efficiency of this load transfer is directly related to the quality of the fiber/matrix bond. The matrix must also isolate the fibers from each other so that they can act as separate entities. In all these structures the volume of fiber architect will depend on the pressure applied on it during the manufacturing of the composite.

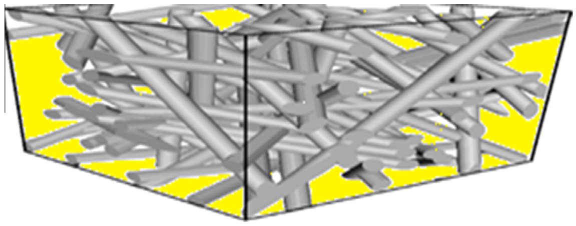

Figure 1 Random fiber architect in composite.

2.1. *Fibrous structures*

Several investigators [2,10,19] indicate that the fiber volume fraction is one of the main parameters in the determination of the NF composite's mechanical properties; consequently we need to determine its exact value. Generally, fiber volume fraction is calculated according to ASTM D2584 as;

$$V_f = [\rho_m \cdot w_f/(\rho_m \cdot w_f + \rho_f \cdot w_m)] \quad (1)$$

where V_f volume fraction of fibers, W_f weight of fibers, W_m weight of matrix, ρ_f density of fibers, ρ_m density of matrix.

2.2. *Effect of moisture content on fiber density*

The natural fibers are affected by the absorption of moisture in two directions; it changes the fiber density through the weight of water absorbed as well as the swelling of fiber itself. The real fiber weight W_f should be modified by W_{f1};

$$W_{f1} = W_f(1 - W_c) \quad (2)$$

where W_c weight of water content, ρ_f density of fibers, ρ_{f0} density of dry fibers. The value of the fiber density ρ_f measured should be corrected, according to the value of the moisture content MC, to be ρ_{fc};

$$\rho_{fc} = (1 + MC)/((1/\rho_{f0}) + MC)) \quad (3)$$

Hence, the Eq. (1) will be;

$$V_f = [\rho_m \cdot W_{fc}/(\rho_m \cdot W_{fc} + \rho_{fc} \cdot W_m)] \quad (4)$$

Fig. 2 shows how the fiber density will change with the moisture content. Consequently, the moisture content problem should be taken into consideration when estimating the fiber volume density.

2.3. *Effect of laid fiber arrangement*

2.3.1. *Ideal fibers assembly*

Assuming that the fiber structure consists of fibers of circular cross section of radius r, two different packing arrangements were considered, open packing and hexagonal close packing [13,16]. Hexagonal close packing is illustrated in Fig. 3, its maximum value is 0.785. For the square packing of the fiber, its maximum value will reach 0.887 [10].

When a matrix is formed of random orientation, the value of volume fraction is reduced depending on the spacing ratio R/r. In this case, the fiber volume fraction may be given by;

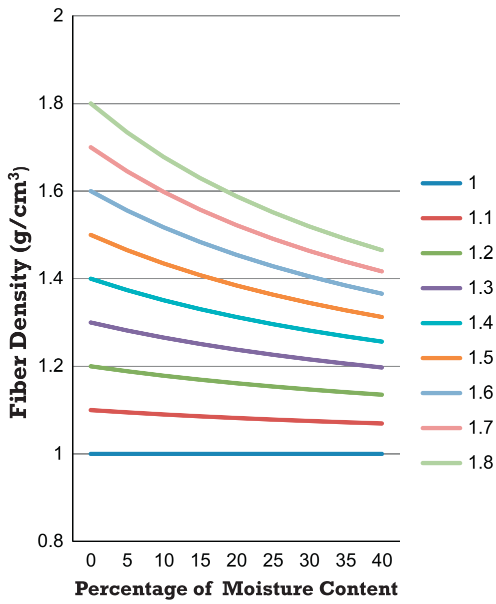

Figure 2 Effect of the moisture content on the fiber measured density.

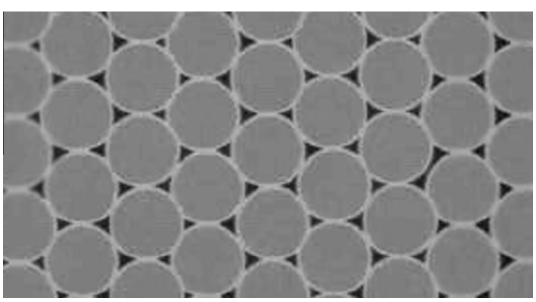

Figure 3 Hexagonal close packing fiber arrangement in composite cross section.

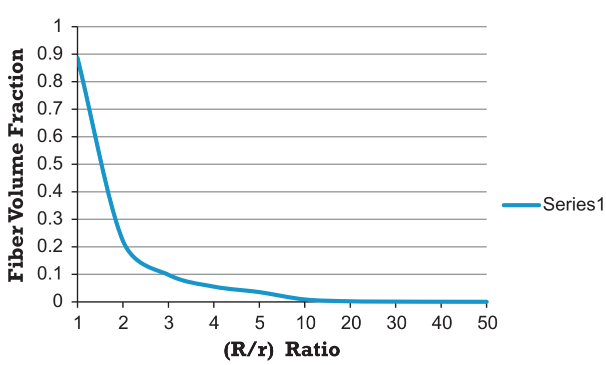

Figure 4 Fiber volume fraction versus the spacing ratio (R/r).

$$V_f = (r/R)^2 \cdot V_{f\max} \tag{5}$$

Where fiber spacing R is the radius of the composite (see Fig. 4).

Fig. 4 shows that the V_f reaches its maximum value when R is equal to r and will decrease rapidly with the increase of (R/r). Gibson [19] indicates that typical fiber volume fractions are only 20–40% for NF. As shown in Fig. 5, the value of (R/r) in some areas may be higher than 3–5.

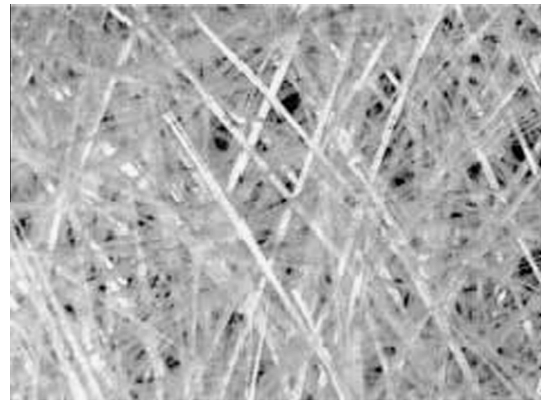

Figure 5 Random arrangement of fibers.

2.3.2. Fiber arrangement in the yarn

In the case of the use of spun yarns as a structural material to form the NF composite, the value of the fiber volume fraction is not the same as in the case of the continues yarn arrangement due to the many reasons such as; the fibers are varied in diameter and cross section shapes as well as its rigidity, the fibers are not straight and parallel but they migrate between the cross section of the yarn along its length, yarn is twisted to get its integrity which will exert a radial pressure on the different fibers in the yarn cross section, make the distribution of the fibers varied and, consequently yarn packing density, the yarn irregularities along the yarn make the diameter of the yarns varied too, the more the diameter, the less will be fiber packing density across the yarn cross section, also each spinning system producing yarns of different structures as well as different packing density. Fig. 6 shows a cross section in a spun yarn.

The above analysis indicates that there is a need to determine the value of fiber volume fraction for the real yarn. Fiber packing density of idealized yarn structures and the distribution of the fiber in the yarn cross section was studied by several investigators [10,13–18]. The packing density may be defined as; the ratio of the volume of fibers to the volume of yarns, the ratio of yarn density to fiber density, the ratio of total cross-section area of fibers to the cross-sectional area of the

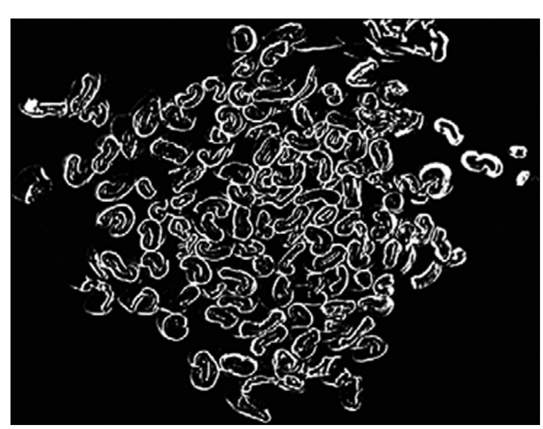

Figure 6 Cross section in a spun yarn.

yarn. Assuming that the yarn is divided into rings of radius r_i so that the areas of such rings are equal, then average value of fiber volume fraction of yarn is;

$$V_f = [\sum(A_{fi}/A_i)]/m \quad \text{For} \quad i = 1, \ldots, m, \tag{6}$$

where m number of the rings, A_{fi} area of fibers in the ring of ith which has an area A_i. If the values of the packing density for a certain yarn are equal to 0.7, 0.6, 0.5, 0.42, and 0.25, respectively for five consecutive rings, the average fiber volume fraction will be 0.494. In this analysis we assume that the yarn diameter is circular and constant along its axis. For theoretical determination of yarn fiber volume fraction, a number of different model forms were tried. Fiber distributions have been studied by a several sources [10,13–18]. The parabolic model [14] fits a wide variety of yarn types, including hollow-centered bundles used in the production of yarns. For yarns that are not hollow-centered, a simplified form of the parabolic equation for the determination of the radial yarn packing density is given by the following equation;

$$V_f(r) = V_{f\max}(1 - (r/R)^2) \tag{7}$$

In the case of idealized structure, the maximum value of $V_{f\max}$ has been proved to be varied between 0.785 and 0.887 [10] depending on the arrangement of the fibers. In the case of real yarns, we can consider $V_{f\max}$ at the center of the yarn. When the yarn is ideally formed in the case of real yarn, there is minimum number of fibers $n_{\min}$ required for its formation [8,20]. This minimum value depends on the spinning system which is defined by the factor (γ). Consequently, the value of the maximum packing density will be less. Hence, the expected maximum packing density in yarn will be given by the following equation;

$$V'_{f\max} = \gamma(n_{\min}/n_y)^{0.5} * V_{\max} \tag{8}$$

where n_y = tex(y) * 10/dtex(F), γ a factor depending on the spinning system. A suitable value of γ for carded ring spinning is 1, for combed ring spinning 1.1, and for compact spinning 1.2.

Fig. 7 illustrates the radial distribution of the fiber volume fraction across the yarn cross section for yarn counts 10, 20, 30 tex, while Fig. 8 shows that the theoretical results of this study are in a good matching with the experimental results by Kremenakova [14], thus supporting the accuracy of the Eq. (8).

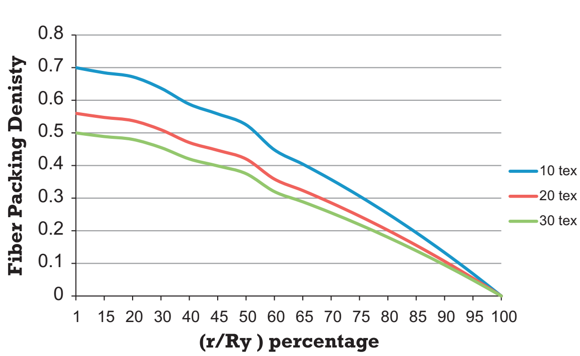

Figure 7 Distribution of fiber volume fraction across the yarn cross section for ring spun yarn counts 10tex, 20tex, and 30tex.

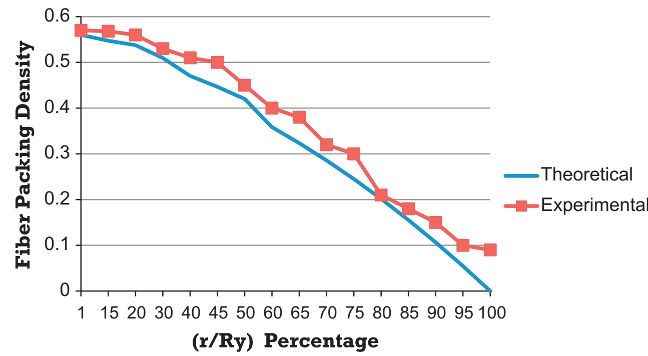

Figure 8 Theoretical and experimental distribution of fiber volume fraction across the yarn cross section for ring spun yarn count 10tex.

From the Eq. (8) we can get the distribution of the fiber volume fraction across the yarn cross section. The average value is given by;

$$V_f = \int V_f(r)dr \Big/ \int dr \tag{9}$$

$$= 0.67 V_{f\max} \tag{10}$$

Assuming that the variation of the yarn diameter is proportional to the variation of the number of fibers in the yarn cross section, that means that the variation of the V_f will follow the same pattern, thick places will have lower value of V_f and thin places will have higher packing density. This is beside the effect of the twist in the thin places zone which will increase the likelihood to get more compact zone. The coefficient of diameter variation is a function of yarn count and varies between 8% and 14% for cotton yarns, for the flax yarns higher values are expected [23].

The variation of the fiber volume fraction value in the NF composite will affect strongly the behavior of its failure. It has been a well known mechanism that when a fiber composite is under an axial tension, the axial displacements in the fiber and in the matrix will be different because of the differences in tensile properties of these two components. As a result, shear strains will be created on all planes parallel to the axes of the fibers. The shear strain and the resulting shear stress are the primary means by which load is transferred to fibers (for a short fiber composite), or distributed between and supported by the two components of composites. Ning Pan [10] pointed out that this interaction between fibers and matrix means fiber reinforcing function is realized. Therefore, it is expected that variation of the fiber volume ratio will result in a variation of the stress along the yarn. Added to that, the effect of fiber orientation in the yarn structure and the presence of the fiber hairiness are not as regular. This will lead to the recommendation of using a regular, open structure yarn with lower packing density and less twist which will give better and low variability of the NF composite mechanical properties.

2.3.3. *Fiber volume fraction in the fabrics*

Architect composite can be formed from one laminate of parallel yarns in one dimension and multilayered composite laminate can be formed using one dimensional laminates laid in

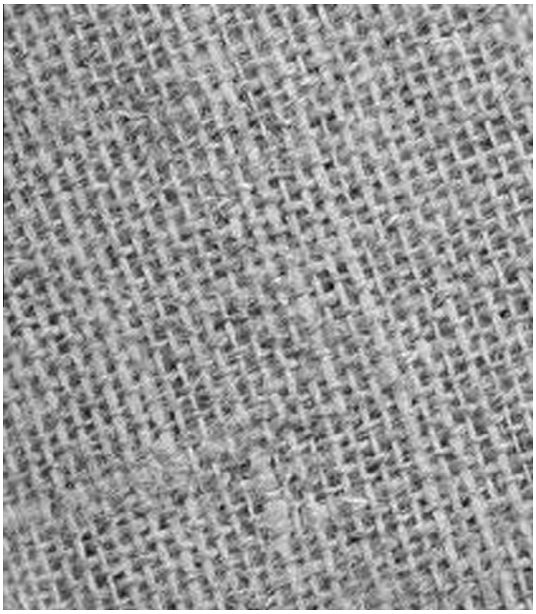

Figure 9 Flax fabric plain weave structure.

different direction on each other. Also yarns can be woven in forms of 2D fabrics or 3D fabrics when thick composites are needed. To overcome the delimitation of the composite, the weave of the yarns may be orthogonal (pain weave) multidirectional fabric, weft knitted, warp knitting, biaxial braided fabric and tri-axial braided fabric. The yarns with fiber volume fraction and when they are architected in a certain structure, the total fiber volume fraction will depend upon the spaces between the yarns in the fabric form. Plain weave of flax fiber, as shown in Fig. 9, clears that the determination of the area between yarns in the fabric is not sufficient to calculate the fiber volume fraction as the yarns will be filled by the matrix material. Consequently, the fiber volume fraction will be;

$$V_f = (\text{Volume of the fiber in the yarns/whole assembly volume}) \tag{11}$$

$$V_f = [\rho_m \cdot w_y / (\rho_m \cdot w_y + \rho_y \cdot w_m)] \tag{12}$$

where ρ_y yarn density, ρ_m matrix material density, w_y weight of yarns, w_m weight of matrix.

The average yarn density can be calculated from the Eqs. (3) and (10). The exact theoretical value of the fiber volume fraction in the case of fabrics has been studied by several investigators especially when continuous synthetic yarns are used for the formation of the fabric. However, it is not in the case of natural fiber yarns with its variability. Thus, we suggest measuring the porosity of the fiber structure in order to determine matrix volume. Porosity and air permeability have a significant correlation [21–24]. The measured value of the air permeability of the fabric or any fibrous structure can be used to calculate the structure porosity, both vertical and horizontal [24].

3. Conclusion

This study aimed to provide a better understanding of fiber volume fraction in natural fiber composites. Fiber volume fraction is affected by the geometric parameters of fiber arrangement within the fibrous structure, the spacing between fibers, and their orientation. A theoretical investigation for factors affecting the fiber volume portion in different cases, fibrous yarn, and fabric structures are formulated. This will lead to the recommendation of using a regular, open structure yarn with lower packing density and less twist which will give better and low variability of the NF composite mechanical properties.

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